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~~Presently~~ seat back angles of 13°, 18°, and 30° from the vertical are found respectively in the F-15, YF-17, and YF-16 fighter aircraft. Theoretically, the reasons for the departure from the standard 13° seat by the YF-16 and 17 are increases in pilot comfort, target visibility, performance, and G tolerance. ~~Consequently~~, the following objective and subjective physiologic parameters were examined relative to seat back angles of 23°, 28°, and 40° (seat angle +10°)

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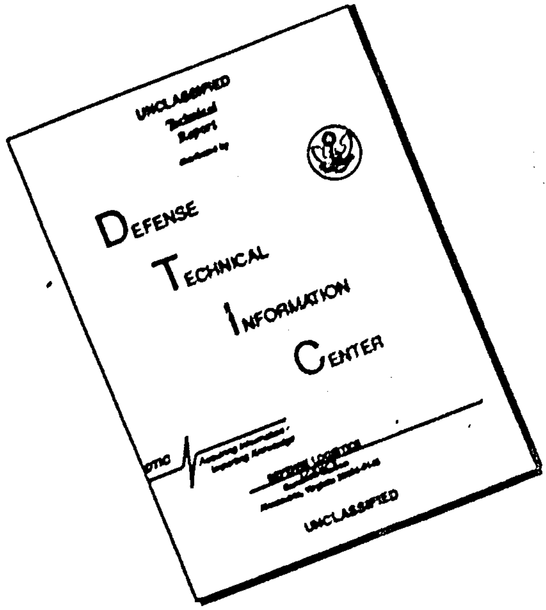

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angle of attack); heart rate and rhythm; arterial oxygen saturation; performance; intrathoracic (esophageal) pressure; arterial pressure; and, subject evaluation of comfort, effort, and fatigue. Eight experimental subjects from the USAF School of Aerospace Medicine (SAM) and four YF-16/17 test pilots were exposed to a simulated aerial combat maneuver (SACM) which included 12 s of 8 G. Relaxed and straining high sustained G (HSG) tolerances (6 G for 60 s) were also determined using only SAM subjects. The advantages of the 30° back angle seat during the SACM included increased subject comfort, less fatigue and effort, a statistically significant reduction in the increased mean heart rate associated with G exposure, and greater pilot acceptance. On the other hand, a statistically significant reduction in arterial oxygen saturation was found during the SACM at 40° compared with the 23° back angle although this seat back angle difference was not found during the HSG exposures. An increase in relaxed G tolerance was found with the 40° seat back angle--statistically significant only compared with the 28° back angle seat. ~~It is concluded that~~ a significant physiologic advantage against G may be gained by increasing seat back angles < 45°.

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Physiologic Effects of Seatback Angles <45° (from the Vertical) Relative to G

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BURTON, R. R., P. F. IAMPIETRO, and S. D. LEVERETT, JR. *Physiologic effects of seatback angles <45° (from the vertical) relative to G.* Aviat. Space Environ. Med. 46(7):887-897, 1975.

Eight experimental subjects from the USAF School of Aerospace Medicine (SAM) and four YF-16/17 test pilots were exposed to a simulated aerial combat maneuver (SACM) which included a maximum G exposure of 6 s at 8 G. The following physiologic parameters were examined relative to seatback angles of 23°, 28°, and 40°: heart rate and rhythm; arterial oxygen saturation; performance; intrathoracic (esophageal) pressure; arterial pressure; and subject comfort, effort, and fatigue. Relaxed and straining high sustained G (HSG) tolerances (6 G for 60 s) were also determined using only SAM subjects. The advantages of the 40° seatback angle during the SACM included increased subject comfort, less fatigue and effort, greater pilot acceptance and a statistically significant reduction in the increased mean heart rate associated with G exposure. On the other hand, a statistically significant reduction in arterial oxygen saturation was obtained during the SACM at 40° compared with the 23° back angle. An increase in relaxed G tolerance was found with the 40° seatback angle—statistically significant only compared with the 28° seatback angle.

PRESENTLY, three seatback angles (13°, 18°, and 30° from the vertical) being considered in advanced air combat fighters are found respectively in the F-15, YF-17, and YF-16 fighter aircraft. The apparent reasons for the departure from the standard 13° seatback angle by the YF-16 and 17 are potential increases in pilot comfort, target visibility, performance, and G tolerance. Of particular interest to our group (Biodynamics Branch, Environmental Sciences Division) at the USAF School of Aerospace Medicine (SAM), Brooks AFB, Tx, are the changes in the pilot's G tolerance and comfort. Accordingly, several objective and subjective physiologic parameters were examined using seatback angles of 23°, 28°, and 40° (seat angle +10° angle of attack). Experimental SAM subjects and YF-16/17 test pilots were exposed to a variable G* profile—aerial combat maneuver (SACM)—using the 6.1-m (20-ft) radius USAFSAM centrifuge. Relaxed and high sustained G (HSG) tolerances also were determined, but using only SAM subjects.

The duty assignment of P. F. Iampietro is AFOSR/NL, 1400 Wilson Blvd., Arlington, Va.

The voluntary informed consent of the subjects used in this research was obtained in accordance with AFR 80-33.

The research reported in this paper was conducted by personnel of the Environmental Sciences Division, Biodynamics Branch, USAF School of Aerospace Medicine, Aerospace Medical Division, AFSC, United States Air Force, Brooks AFB, Tx.

MATERIALS AND METHODS

Inasmuch as the main reason for this experiment was application to pilots of high-performance aircraft, four members of the test-pilot team for the YF-16 and 17 were used as one group of subjects. Another group of men—residents at SAM and experienced centrifuge riders—also was used in the experiment since it was possible to subject them to more a) detailed physiologic measurements and b) acceptable experimental design. Consequently the methods and results are presented relative to the appropriate subject population.

SAM Subjects: Eight men, qualified for acceleration exposure after passing a Class II flying physical, were trained to tolerate high $+G_z$ exposure using the standard 5-bladder USAF anti-G suit (CSU-13A/P) and performing the anti-G straining M-1 or L-1 maneuvers. Their ages ranged from 21 to 34 years (mean of 25.0 years) and they weighed 64 to 87 kg (mean of 74.3 kg). For details regarding human exposure to high G on the centrifuge at SAM, selection and training of subjects, and anti-G techniques, the reader is referred to a recent review article by Burton *et al.* (6). Since this experiment required exposure to a variable G profile (SACM) and the use of a target-tracking task, the men were given additional training in these specific areas.

Each subject was exposed to the same SACM** once a day (Fig. 1). On another day, five of the eight sub-

*The G exposures used in this experiment are principally $+G_z$ relative to the long axis of the subject. However, as the seatback angle is increased from the vertically directed G forces of the centrifuge, more of the $+G_x$ component involves the total resultant G vector relative to the subject. For this reason, the symbol "G" (without the vector symbols) only will be used in this text. Regarding acceleration nomenclature the reader is referred to Kaufman (13).

**The simulated aerial combat maneuver used in this experiment (SACM) approximates an actual F-4E aerial combat maneuver with modifications suggested by the test pilots and considered more appropriate for these newer fighter aircraft.

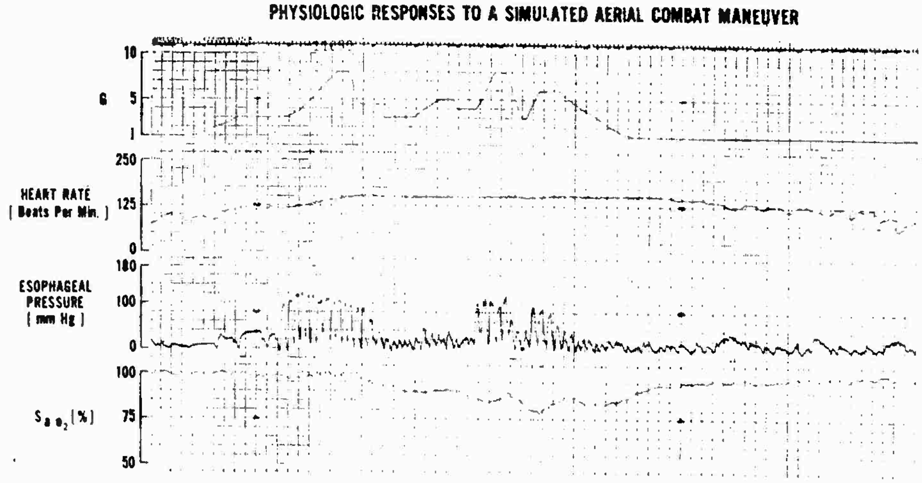

Fig. 1. An example of three physiologic responses (heart rate, esophageal pressure, arterial saturation) of one subject exposed to the simulated aerial combat maneuver (SACM). The SACM used in this experiment was approximately 95-s duration and included 6 s of 8 G. The mean G level of this maneuver was 4.8 G.

jects were exposed to HSG (constant 6 G for 60 s with onset rates of 1 G/s, known as rapid onset rates, ROR). Also, the eight subjects were exposed to a series of "relaxed" 15-s G exposures (ROR and onset rates of 0.1 G/s, known as gradual onset rates, GOR) to determine their relaxed tolerances—with and without anti-G suit inflations—for each seatback angle. Methods used in determining relaxed $+G_z$ tolerances have been described previously (8). A minimum of 2 d of rest was allowed between G exposures. Each man was exposed to a total of three SACMs and three HSG runs, with each exposure at a different seatback angle—the specific back angle used was randomized relative to number of exposure.

Prior to each SACM exposure, 3 min of pre-G data were taken from the subject as he "relaxed" at 1 G. He was then exposed to 15 s of 4 G and allowed to recover to his pre-G heart rate prior to the SACM. This 4-G exposure is used to stimulate the anti-G basic physiologic responses which are helpful in tolerating high $+G_z$ exposures. Relaxed tolerances were determined prior to each HSG run, thereby eliminating the initial 4-G exposure. After the high-G runs, the subject remained in the centrifuge gondola for continuous monitoring of his physiologic recovery for 20 min post-SACM and for 10 min post-HSG.

The three seatback angles used in this study were: 23°, 28°, and 40°; each is a sum of the seatback angle found in the appropriate fighter aircraft under consideration plus a 10° "angle of attack." An angle of attack is appropriate for aircraft maneuvers but, of course, is not present in G exposures using a centrifuge.†

† The angle of attack ("α") usually—but not always since α may be negative—adds to the seatback angle which the pilot experiences. A further complication—which is unattainable on the centrifuge—regarding a simulation is that it is highly variable during aircraft maneuvers. We were advised to use a constant $+10°$ α which was built into the seatback angle. The possibility of other acceleration vectors associated with aircraft was considered by the investigators but could not be simulated with this centrifuge, although it is doubtful that these accelerations would contribute significantly to the G tolerance of the pilot.

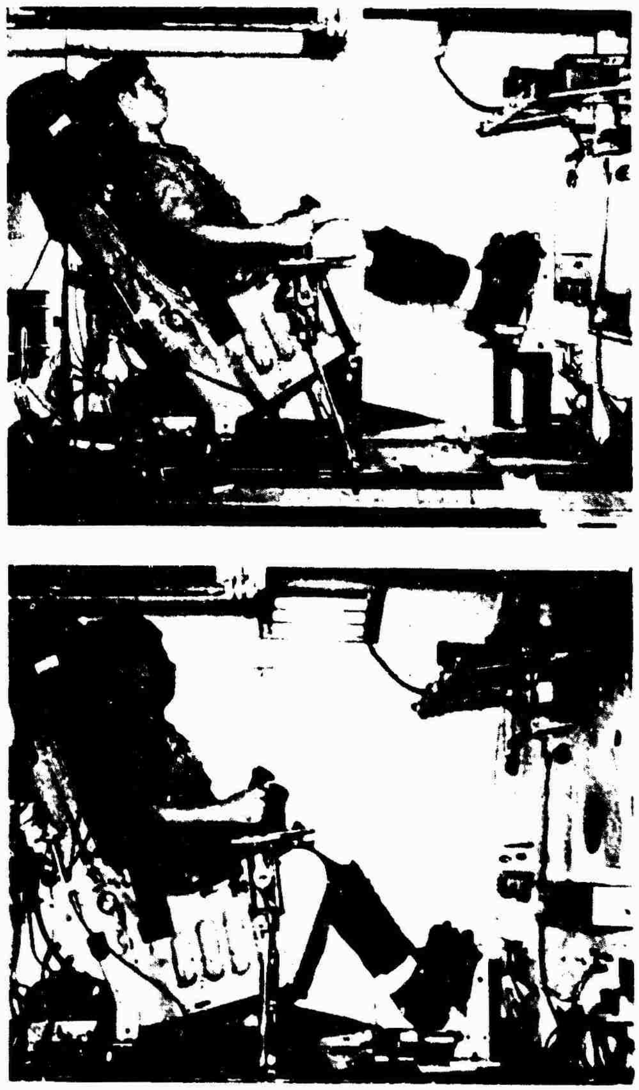

Fig. 2. Subject in the seat with a back angle of 40° with feet elevated (above). Seat back angle at 23° with feet nearer the floor (below).

Foot position—heel-line relative to the seat pan—approximated that of the appropriate aircraft. Specifically, the "rudder-pedals" were elevated the same in the 28° and 40° seatback angles so that the heel-line was approximately 5.0 cm (2 in) below the level of the seat pan. The foot position in the 23° seatback angle used the same "rudder pedals;" however, these were located nearer the floor of the gondola approximately 30 cm (12 in) below the seat pan (Fig. 2).

Parameters determined with these subjects included: heart rate and rhythm, arterial blood pressure, esophageal (intrathoracic) pressure, arterial oxygen saturation, performance (SACM portion only), and subjective analyses relative to seat comfort, effort required during G exposure, fatigue, and recovery from fatigue after G exposure.

Heart rate and rhythm were determined from the electrocardiogram (ECG) resulting from sternal and biaxillary leads. Arterial blood pressure was measured before and after the G exposure using indirect pneumatic cuff Piezo crystal microphonic methods every 30 s (10). Esophageal pressure was determined during SACM and HSG using an esophageal balloon swallowed by the subject via the nasal passage to approximately heart level and attached to a Statham (P23De) pressure transducer. Oxygen saturation was approximated indirectly using an ear-type oximeter designed specifically for use during G exposure. A prototype of this ear oximeter has been described previously (16).††

The target-tracking task is a modification of the task previously reported by Burton and Jaggars (3). The target appears as an electronic "+" on the scope in front of the subject in the centrifuge gondola and is automatically driven toward the periphery of the scope by the change in acceleration which occurs during the SACM. An increase in G moves the target upward (toward 12 o'clock) and a decrease in G has a reverse effect. The acceleration drive of the target, however, may be negated by manual movement by the subject of the "stick," located on the right arm of the aircraft seat (Fig. 2). This side-arm location of the stick allows the subject to reach it at the greater seatback angles; e.g., a side-arm control is standard in the YF-16. This stick location, however, was not altered with a change in seatback angle since our primary interest was in seatback angle, and a change of stick location would have introduced an uncontrolled experimental variable. The subject attempts to keep the target in the center of the scope—where a "gunsight" is painted—by moving the "stick" towards himself during increasing G and away during a reduction of G. The performance score was continually monitored during the SACM relative to error—graded as the distance of the target from the center of the scope. This task was not used during HSG exposures.

Subjective analyses were determined after G exposures (during the recovery stage) using prepared cards which the subject marked relative to their level of: a) comfort during the ride, b) physical effort required to maintain vision (M-1 or L-1), and c) fatigue which the subject was presently experiencing (Fig. 3). A fatigue score card was presented to the subject immediately and every 5-min post-G for the entire recovery period in order to subjectively measure fatigue recovery. After the last SACM exposure, each subject was asked to list the seatback angles as to their overall preference during G exposure.

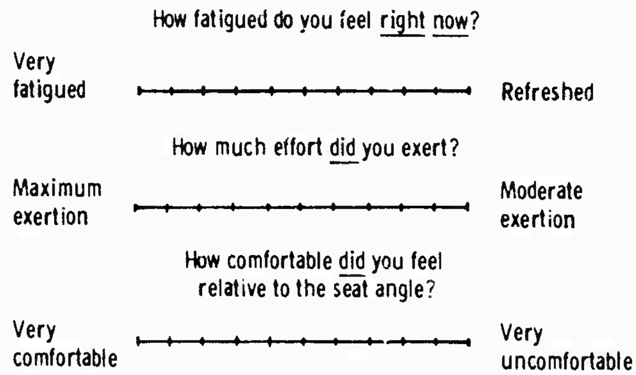

Fig. 3. This is a composite of the three cards presented to the subjects and pilots immediately after G exposure. The upper fatigue card was also presented at 5-min intervals post-G exposure.

Light loss phenomena were used as the criteria of termination of G for all acceleration exposures—viz 100% peripheral light loss (PLL) and 50% central light loss (central light dim, CLD)—although the subjects usually maintained a light loss level during SACM and HSG of approximately 50% PLL.

The analog data were recorded on a Mark 200 Brush recorder and simultaneously taped on a Model 4742 Sangamo recorder for later computer analysis.

Pilot Subjects: Four test pilots of the YF-16 and 17 test team from Edwards AFB, Ca, were subjected to the same SACM profile and randomized seatback angles as were our SAM subjects, except the three exposures to G were accomplished on the same day with only a 20-min recovery period between runs.

The same parameters were monitored for the pilots as for our SAM subjects, except for esophageal pressure. The pilots were not exposed to HSG nor were we able to measure their relaxed G tolerance.

After exposure to the three SACM, the pilots subjectively evaluated the experiment relative to the degree of excellence as a simulation of an ACM in the YF-16 and 17 relative to: a) seat position; b) rudder pedal location; c) stick position (applicable to YF-16 only); and, d) G profile using the target-tracking task as an actual ACM.

RESULTS

Relaxed G Tolerance

The effect of seatback angles of 23°, 28°, and 40° upon relaxed ROR and GOR tolerances of individual SAM subjects, with and without anti-G suit inflation, is

††Even earlier, photoelectric techniques were used to quantitate ear opacity during G exposure, thereby obtaining some estimation of Sao_2 (18).

shown in Table I. Relaxed mean tolerances increased 0.3—0.4 G at 40° compared with the 23° seatback angle, although this increase in tolerance was not statistically significant (paired t-test); viz the increase in tolerance at 40° was not apparent with every person—JR and MM appeared to actually have a slight decrease in G tolerance at 40°. Interestingly, because of a slight decrease in G tolerance for the 28° back angle, G tolerances for the 40° seatback angle were significantly increased ($p<0.05$; paired t-test) over the 28° seatback angle in both the GOR and ROR (anti-G suit on, but not inflated) groups.

Burns (2) previously had reported a statistically insignificant reduction in relaxed ROR tolerance at a 30° seatback angle compared with his control (13°) group. Yet at 45°, a seatback angle 5° greater than the 40° reported in this study, Burns (2) found relaxed tolerances to be significantly greater than at 13°. Considering both studies, it appears that a slight decrease in G tolerance is apparent in the seatback angle range >23° and <40° and that significant increases in relaxed G tolerances over the 13° seatback angle are not possible below 45°; i.e., not even 40° with elevated lower legs and feet (Fig. 2).

Physiologic Responses Associated With High G

Tolerance to G levels above 5 G, even with the aid of an inflated anti-G suit, requires well-coordinated physical activity commonly referred to as an M-1 or L-1 maneuver (6). Inasmuch as this activity requires muscular tensing, forced exhalation, and some degree of mental acuity while the subject is at high G, only physiologic monitoring devices were used which were not cumbersome; i.e., an attempt was made to relate our findings to a pilot flying a high-performance aircraft.

Pilot acceptance of our laboratory experiment as an adequate simulation of an aerial combat maneuver in an aircraft was considered in detail in this study. The four pilots considered our experiment as acceptable regarding 88% of the criteria outlined in the Methods section of this text.

TABLE I. RELAXED TOLERANCES, BOTH GOR AND ROR (ANTI-G SUIT INFLATED AND NOT INFLATED), FOR 8 MEN AT 3 DIFFERENT SEATBACK ANGLES.

	Seatback Angle								
	23°			28°			40°		
Subject	ROR		GOR	ROR		GOR	ROR		GOR
	NP*	P*	NP	NP	P	NP	NP	P	NP
RR	4.0	5.1	4.3	3.8	5.0	4.3	5.0	5.8	5.8
JK	—	—	—	4.0	5.2	4.8	4.2	5.7	4.8
JR	4.3	5.8	4.7	4.0	6.0	4.7	4.0	5.5	5.0
DE	3.6	5.5	5.0	3.9	5.4	4.9	3.8	5.8	5.3
CK	3.8	5.4	4.7	3.4	4.6	3.9	4.0	5.4	4.4
SS	3.0	4.0	3.7	3.0	4.0	3.6	3.4	4.4	4.3
MM	4.1	4.9	4.2	3.4	5.1	3.9	3.8	5.0	3.8
DS	4.0	5.4	4.9	3.8	4.7	4.3	4.4	6.0	5.4
Mean	3.8	5.2	4.5	3.7	5.0	4.3	4.1**	5.5	4.9**
SE	0.16	0.22	0.17	0.13	0.21	0.17	0.17	0.19	0.21

* NP = anti-G suit on but not pressurized; P = standard anti-G suit pressurization (1.5 psi/G beginning at 2 G); ** Significantly different, $p<0.05$ (paired t-test), compared with 28°.

Pre-G Sympathetic Response: Mean heart rates for a 3-min period immediately prior to high-G exposure for the SACM and HSG are shown in Table II relative to seatback angle. Since prestress heart rates are considered a criterion of psychologic activity (1,6)—response directly correlated to the degree of anticipated stress—it was thought that subject confidence in the anti-G effect of a particular seatback angle would alleviate his "fears" and this would be reflected in a lower pre-G heart rate. Both the pilots and SAM subjects had considerable experience with these various seatback angles so they were fully aware of the existence of any significant anti-G effect. It appears that both the SAM subjects and pilots were equally prestressed at all seatback angles prior to the SACM or HSG exposure.

Cardiovascular Work: Cardiovascular work was quantified during the SACM and HSG using mean heart rate for the entire G exposure (Table III). Mean heart rate for SAM subjects during the SACM at 40° seatback angle was, statistically, significantly less (paired t-testing; $p<0.01$) compared with the 23° angle. The same trend, although not statistically significant ($p>0.05$), was apparent during HSG exposure. Interestingly, the pilots' heart rates were not correlated with seatback angle; however, the pilots were observed to sit erect in the seat and not rest their upper torso and head against the back of the seat—they did not take advantage of the greater back angle; i.e., the pilots were asked to sit with a posture they assumed during aircraft maneuvering (Fig. 4). On the other hand, the SAM subjects were instructed to rest their back and head against the seat, thereby reducing their eye-heart vertical distance—theoretically allowing the back angle to achieve its greatest anti-G effect (Fig. 2).

Heart rates obtained from the SAM subjects during exposure to the two 8-G epochs during the SACM

TABLE II. MEAN HEART RATES (±S.E.) PRIOR TO G EXPOSURE RELATIVE TO SEATBACK ANGLE.

		Seatback Angle		
G exposure	N*	23°	28°	40°
SACM	8	85.4 ± 3.11	82.9 ± 3.98	86.3 ± 3.37
HSG	5	84.8 ± 3.06	81.8 ± 3.57	84.4 ± 4.98
SACM**	4	86.3 ± 3.94	83.3 ± 6.80	82.0 ± 5.11

*N = Number of subjects per group

** Pilots were subjects.

TABLE III. MEAN HEART RATES (±S.E.) DURING G EXPOSURES RELATIVE TO SEATBACK ANGLE.

		Seatback Angle		
G exposure	N*	23°	28°	40°
SACM	8	153.5 ± 6.03	148.5 ± 5.77	145.4 ± 5.86†
HSG	5	152.6 ± 5.53	148.2 ± 8.53	141.8 ± 9.94
SACM**	4	139.8 ± 9.29	135.3 ± 2.06	144.8 ± 4.19

*N = Number of subjects per group.

** Pilots were subjects.

† = Significantly different from heart rates at 23° using paired t-testing ($p<0.01$).

Fig. 4. A YF-16/17 test pilot is shown demonstrating the seated posture used by him on maneuvers in the YF-17 (18° seatback angle).

(Fig. 1) were quite interesting relative to back angle. During the first 8-G episode, mean heart rates (±S.E.) were not significantly different between seatback angle groups; viz, 23° (167±6.7), 28° (164±4.8), and 40° (162±8.8). However, during the second 8-G exposure, mean heart rates for the 23° group had increased to 170±5.7 and the 40° group had decreased to 158±6.3 (statistically significant; paired t-test $p < 0.05$), while the 28° group remained about the same at 163±4.7. An example of heart rates obtained during an SACM is shown in Fig. 1.

Cardiovascular stress: Cardiovascular stress was examined using the ECG and identifying cardiac arrhythmias which occurred during exposure to high G. Non-serious type cardiac arrhythmias commonly are associated with high-G exposure (6).

In this study, two types of cardiac arrhythmias were occasionally found; viz a) premature ventricular contractions (PVC) and b) junctional block (JB). The incidence of these arrhythmias relative to seatback angle, considering individual subjects and pilots, is shown in Table IV. The occurrence of cardiac arrhythmias appears to be associated with: a) the individual and b) the frequency of high-G exposure. There is no suggestion that these arrhythmic beats are correlated with a particular seatback angle.

Regarding individual susceptibility, of the 12 subjects (including four pilots) five had no arrhythmic beats; of the total arrhythmias of 58, one subject had 18 (31%) and 2 pilots had 21 (36%); i.e., 67% of the total arrhythmic beats were observed to occur in 25% of the subjects.

Repetition of G exposure within the same day also appears to be important regarding cardiac arrhythmias. The pilots, as noted earlier under Methods, were exposed to three identical SACMs on the same day. Two of these four pilots had arrhythmic beats and these were directly correlated with the number of the SACM: exposure 1=2 JB; exposure 2=7 JB; and exposure 3=9 JB and a series of 3 PVCs.

TABLE IV. CARDIAC ARRHYTHMIAS OBSERVED RELATIVE TO SEATBACK ANGLE.

		SACM		
Subject		23°	28°	40°
RR		1 PVC*	2 J*	0
JK		0	0	0
JR		0	0	5 J
DE		7 PVC	2 PVC/1J	4 PVC
CK		0	0	0
SS		0	0	0
MM		1 PVC	0	0
DS		0	0	0
Total	PVC*	9	2	4
	J*	0	3	5
	All	9 (1.1)†	5 (0.6)	9 (1.1)
Pilots				
1		0	0	0
2		0	0	0
3		2 J	3 PVC**	0
4		9 J	5 J	2 J
Total	PVC	0	3	0
	J	11	5	2
	All	11 (2.8)	8 (2.0)	2 (0.5)
Subjects			HSG	
JR		0	0	1 PVC, 2J
DE		1 PVC	0	4 PVC**
CK		0	0	0
MM		0	0	0
DS		1 J	1 J	0
Total	PVC	1	0	5
	J	1	1	2
	All	2 (0.4)	1 (0.2)	7 (1.4)
Total††		22 (1.3)	12 (0.7)	18 (1.1)

* PVC = premature ventricular contraction; J = Junctional block.
** in pairs (bigeminal)
† = mean arrhythmic beats/subject
†† = Total arrhythmic beats for entire study (mean arrhythmic beats/subject in parenthesis).

TABLE V. LOWEST ARTERIAL OXYGEN PERCENT SATURATION (MEAN ± S.E.) FOUND DURING G EXPOSURE RELATIVE TO SEATBACK ANGLE.

		Seatback Angle		
G exposure	N*	23°	28°	40°
SACM	8	86.0 ± 1.75	83.4 ± 3.21	79.4 ± 4.21†
HSG	5	79.5 ± 1.85	75.2 ± 5.16	75.2 ± 5.76
SACM**	4	83.0 ± 0.82	83.0 ± 1.58	84.5 ± 2.40

*N = number of subjects per group
** Pilots were subjects
† = Significantly different from oxygen saturations at 23° using paired t-testing ($p < 0.01$)

Arterial Oxygen Saturation: The effects of seatback angles on arterial oxygen saturation, Sa_{O_2}, during high G are shown in Table V. The lowest Sa_{O_2} occurred at the termination of the SACM (Fig. 1) or HSG exposures and these values were used to calculate group means ± SE found in Table V. The mean Sa_{O_2} of SAM subjects exposed to the SACM at 40° back angle (79.4%) was lower than found for the same men at back angles of 23° and 28°—statistically so at 23° (paired t-test; $p<0.01$). This relatively high O_2 desaturation at

40°, however, is not so apparent in five of these same subjects during HSG. The reason for this inconsistency is not apparent. Since the seatback angle response regarding Sa_{O_2} disappears during a constant G environment, the differential effect found between HSG and the SACM appears to be a function of changing G. This oxygen saturation response relative to the dynamic G environment of the SACM is being considered in detail by Gillingham (10) using Fourier analyses.

The oxygen saturations found in this study using the ear oximeter for the constant 6-G exposures may be compared with previous HSG studies as reviewed by Burton *et al.* (6). They reported rectilinear reductions in Sa_{O_2}—considering group means—with sustained G levels varying from approximately 1.6%/$+G_z$ to 3%/$+G_x$. At 6 G (60 s duration) we found a mean Sa_{O_2} for all three seatback angles of 77% or 3.3% reduction in saturation per G.

Performance

Tracking task performance quantified as mean error for a SACM exposure was not different between subject and pilot populations nor were there significant differences between seatback angles (Table VI).

Effort and Fatigue Associated with High G

Effort and fatigue, including fatigue recovery, will be considered together in this text, since each bears some relationship to the other.

Effort: The effort required by the SAM subjects and pilots to maintain adequate vision was quantified by subjective analysis and, for the SAM subjects only, by an increase in the esophageal (intrathoracic) pressure during high-G exposure.

Subjective Analysis:

The effort expended during exposure to high G was quantified subjectively using a card illustrated in Fig. 3. All three groups found the greater seatback angle allowed them to tolerate either the SACM or HSG with less effort, although only with the 40° seat in the HSG portion of the experiment was this difference found to be statistically significant ($p<0.05$) from the 23° seat (Table VII). The pilots appeared to expend more effort during these exposures than our subjects; however, their effort scores were correlated with their SACM exposure number; viz, exposure 1 = 1.5 (similar to the score of the SAM subjects at 23°); exposure 2 = 1.0; and exposure 3 = 0.75. Apparently some effort/fatigue relationship was evident in the pilot group.

Our conversations and observations with the pilots revealed that their experience with G exposure is quite different from SAM subjects. The pilots can control the G level in an airplane, thereby reducing the G level as their immediate tolerance demands. Since pilot control of the G level was not allowed in this experiment, they probably overworked to prevent the "embarrassment" of blackout. Also, pilots perform straining maneuvers (L-1 and M-1) quite differently than our subjects—it appears that anti-G straining techniques, in the world

TABLE VI. TRACKING TASK PERFORMANCE (QUANTIFIED AS MEAN ERROR) FOUND DURING EXPOSURE TO SACM RELATIVE TO SEATBACK ANGLE (MEAN ± S.E.). HIGH SCORE INDICATES POORER PERFORMANCE.

		Seatback Angle		
Subjects	N*	23°	28°	40°
SAM	8	39.6 ± 7.4	39.7 ± 5.2	40.8 ± 5.4
Pilots	4	33.7 ± 8.6	43.0 ± 9.6	42.4 ± 8.5

* N = number of subjects per group.

TABLE VII. EFFORT (SUBJECTIVE DATA) REQUIRED BY SUBJECT DURING EXPOSURE TO G RELATIVE TO SEATBACK ANGLE (MEAN ± S.E.). (HIGHER SCORE INDICATES LESS EFFORT.)

		Seatback Angle		
G exposure	N*	23°	28°	40°
SACM	8	1.4 ± 0.32	2.9 ± 0.52	3.3 ± 0.82
HSG	5	2.8 ± 0.80	4.6 ± 0.68	5.6 ± 0.98†
SACM**	4	0.8 ± 0.48	1.2 ± 0.75	1.2 ± 0.48

* N = Number of subjects per group.
** Pilots were subjects.
† = Significantly different compared with 23° seat angle (paired t-test; $p < 0.05$).

TABLE VIII. MEAN ESOPHAGEAL PRESSURES (mm HG) OF SAM SUBJECTS DURING EXPOSURE TO G RELATIVE TO SEATBACK ANGLE.

		Seatback Angle		
G exposure	N*	23°	28°	40°
SACM	8	25.4 ± 1.85	25.0 ± 0.91	28.3 ± 1.60**
HSG	5	54.2 ± 3.81	56.2 ± 4.31	76.4 ± 8.74†

* N = Number of subjects per group.
** $p < 0.05$ vs 23° and 28° seat angle (paired t-test).
† $p < 0.10$ vs 23° seat angle (paired t-test).

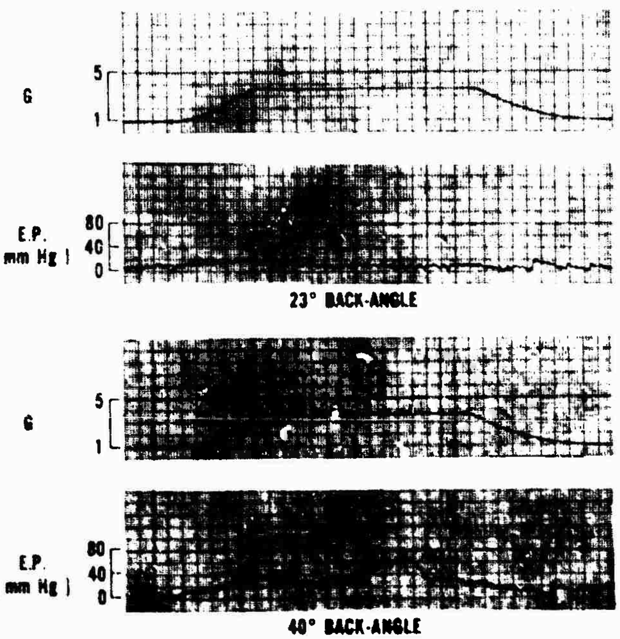

Fig. 5. Eophageal pressure recordings from the same man at 23° and 40° seatback angles while relaxed—anti-G suit on the subject but not inflated—during the same level of G exposure.

of aviation, are varied and appear to be quite individualistic.

Esophageal pressure responses:

Esophageal pressures Pes (mm Hg) were higher in the subjects at 40° than at 23° for both SACM ($p < 0.05$) and HSG (Table VIII). Pes is a quantification of intrathoracic pressure which, in acceleration research, is used to estimate the effort exerted by the subject in performing an M-1 straining maneuver at high G (2,6). The higher Pes associated with the 40° seatback angle therefore suggests more effort was expended by subjects riding at the greater seatback angle. However, the Pes of relaxed subjects wearing an uninflated anti-G suit and exposed to low levels of G was considered relative to their seatback angle; i.e., the Pes was frequently higher (approximately 20 mm Hg) in those persons at 40° and never higher in subjects at 23° (Fig. 5). This observation of greater Pes at 40° was most common during sustained G and became less apparent during a variable G exposure (Table VIII). The mean Pes for a SACM was a function of the maximum Pes which occurred during the 8 G epochs, and here the pressures were not different among the various seatback angles; viz (mean ± S.E.) 23° = 107 ± 7.2; 28° = 102 ± 5.2; and 40° = 110 ± 7.4 mm Hg. An example of the esophageal pressures found in one subject during exposure to the SACM is shown in Fig. 1.

The apparent reason for the measured Pes to be higher at the greater seatback angle of 40°, especially in relaxed subjects and in persons during HSG, is that the contents of the pleural cavity would be bearing its weight (mass) more laterally against the wall of the esophageal balloon transforming this weight into an apparent increased Pes during G. This effect of body position on esophageal pressure measurements has been considered previously in some detail (9). Consequently Pes as an index of effort expended during G exposures must be used with extreme caution, especially at seatback angles >28°.

Another seemingly apparent discrepancy regarding the use of Pes as a quantification of effort is that other parameters used in this study to estimate effort and fatigue—subjective (Table VII), heart rate recovery (Table IX), and blood pressure recovery (Table X)—generally indicated that the SACM was more stressful than exposures to HSG, whereas the mean Pes for the HSG group (23° and 28° seatback angles) was approximately twice that of the SACM group (Table VIII). This may be explained, however, if we consider the relationship of effort to Pes as nonlinear and, instead, exponential—much greater effort and fatigue is associated with an increase in the Pes, especially at levels above 75 mm Hg. Consequently, the subjects during the high-G epochs of the SACM where their pressures were frequently >100 mm Hg, exerted much more effort than would be expected with a simple effort:Pes rectilinear relationship. On the other hand, the 6-G (HSG) exposure never required an extremely high Pes.

Fatigue and Fatigue Recovery. Fatigue and its recovery were considered using two objective physiologic parameters, heart rate and arterial pressure recoveries, and one subjective measurement.

Heart rate recovery:

Heart rate recovery following physiologic stress is frequently used as a method to quantify fatigue—reviewed by Simonson (17) and recently adapted to acceleration research by Burton *et al.* (6). Total heart beats during the recovery phase of physical exertion is termed "erholungspulssume" (EPS), and this was determined for all three groups relative to seatback angle.

The EPS for the SACM was higher than for the HSG

TABLE IX. THE ERHOLUNGSPULSSUME (EPS) FOLLOWING EXPOSURE TO G RELATIVE TO SEATBACK ANGLE (MEAN ± S.E.).

		Seatback Angle		
G exposure	N*	23°	28°	40°
SACM	8	300 ± 57	343 ± 102	406 ± 82
HSG	5	180 ± 57	193 ± 37	153 ± 65
SACM**	4	299 ± 78	263 ± 79	362 ± 107

* N = number of subjects per group.

** Pilots were subjects.

TABLE X. SYSTOLIC ARTERIAL PRESSURE (mm HG) AFTER EXPOSURE TO G RELATIVE TO SEATBACK ANGLE (MEAN ± S.E.).

Seatback angle	30s	60s	120s	180s	240s	300s	480s
			SACM (N* = 8) (Mean ± S.E.)				
23°	181 ± 11	210 ± 5.4	178 ± 5.4	164 ± 3.8	153 ± 1.3	144 ± 2.7	121 ± 1.6
28°	201 ± 9.3	199 ± 5.9	130 ± 5.9	155 ± 4.2	144 ± 3.2	142 ± 3.9	124 ± 3.2
40°	221 ± 3.6†	196 ± 9.9	177 ± 6.3	160 ± 5.9	149 ± 5.0	141 ± 4.2	129 ± 4.2
			HSG (N = 5)				
23°	194 ± 19	204 ± 16	171 ± 8.7	151 ± 3.7	143 ± 4.6	139 ± 5.3	131 ± 5.1
28°	186 ± 10	186 ± 13	162 ± 8.9	143 ± 4.6	132 ± 3.7	127 ± 3.7	123 ± 3.4
40°	169 ± 2.9	183 ± 14	152 ± 9.4	137 ± 4.9†	128 ± 3.7	127 ± 3.7	122 ± 5.8
			SACM** (N = 4)				
23°	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	131 ± 5.6	120 ± 2.9
28°	187 ± 14	178 ± 6.3	171 ± 7.5	161 ± 12	146 ± 9.2	141 ± 9.9	120 ± 3.5
40°	204 ± 15†	181 ± 10	169 ± 7.5	158 ± 8.5	151 ± 8.3	140 ± 2.9	120 ± 2.0

* N = Number of subjects per group.

** Pilots were subjects.

† = Significantly different from 23° seatback angle (paired t-test; $p < 0.05$).

TABLE XI. FATIGUE AND ITS RECOVERY, USING SUBJECTIVE DATA, FOLLOWING EXPOSURE TO G (MEAN ± S.E.). HIGH SCORE INDICATES LESS FATIGUE.

Seatback Angle	0 Min	5 Min	10 Min	15 Min	20 Min
SACM (N = 8)					
23°	5.0 ± 0.8	6.5 ± 0.8	7.8 ± 0.8	8.5 ± 0.7	9.0 ± 0.5
28°	4.9 ± 0.6	6.5 ± 0.8	8.3 ± 0.7	8.9 ± 0.5	9.4 ± 0.3
40°	5.8 ± 0.8	7.5 ± 0.8	9.0 ± 0.3	9.8 ± 0.2	10 ± 0.0
HSG (N = 5)					
23°	3.2 ± 1.01	6.8 ± 1.6	8.4 ± 1.6	Not determined	Not determined
28°	3.0 ± 0.6	7.4 ± 0.7	9.6 ± 0.2		
40°	4.6 ± 0.8*	7.4 ± 0.8	8.6 ± 1.2		
SACM (Pilots; N = 4)					
23°	3.5 ± 1.0	5.0 ± 1.1	6.5 ± 1.0	7.5 ± 1.0	8.3 ± 0.9
28°	4.0 ± 1.1	5.5 ± 1.0	7.3 ± 0.6	7.8 ± 0.8	8.0 ± 0.6
40°	4.8 ± 0.6	6.5 ± 0.9	7.5 ± 1.0	8.3 ± 0.9	8.3 ± 0.9

N = Number of subjects per group.
* = Significantly different from 23° and 28° seatback angle (paired t-test; $p < 0.01$).

exposure suggesting that 60 s of 6 G HSG was less fatiguing than 95 s of a variable 4.8 mean G exposure (Table IX). This correlates well with less effort required during HSG compared with the SACM (Table VII). Both the pilots and subjects had similar EPSs, although the pilots probably were more fatigued than were SAM subjects because they had to tolerate all three SACMs in 1 d. The EPS (as would be expected) is a function of heart rate. Since mean heart rates during G were lower for the pilots during high-G exposure (Table III), equal EPS essentially suggests more fatigue in the pilots. Because of the great dependence of the EPS on heart rate and since heart rate is an individual characteristic, the comparison of the EPS between groups of different subjects is not without some hazard. However, no consistent differences in the EPS of the same subjects between seatback angles are apparent.

Arterial Pressure Recovery:

Systolic arterial pressure recovery was suggested by Leverett *et al.* (14) as a method to quantify fatigue following HSG exposure. It was observed by the Leverett group that systolic pressure overshoots occurred approximately 60 s post-HSG exposure and that these were directly correlated with the duration and intensity of G. Unfortunately, in this experiment we were unable to get direct continuous arterial pressure recordings; consequently our indirect method of sampling occurred but once every 30 s, so that it was impossible to verify the peak arterial pressure (overshoot) post-G in this study. Several interesting observations were made, however, as shown in Table X.

Pressure recoveries (30 s) relative to HSG and SACM are different relative to seatback angle—highest in the 40° seat after SACM (both subjects and pilots) and lowest in the 40° seat following HSG. Considering all seatback angles, however, the pressure overshoot relative to HSG was lower than following the SACM, suggesting once again that the SACM was more fatiguing.

Regarding the SACM observations, however, it appears that the peak overshoot relative to the 23° seatback angle occurred later—systolic pressures of 181 mm Hg at 30 s and 210 mm Hg at 60 s—than found in the 40° seatback angle, suggesting that our method of detecting arterial pressure post-G (sampling techniques), indeed, was not frequent enough to be reliable. The 23° seatback angle-related arterial overshoot occurred later than that found at 40°, suggesting that probably the 23° seatback angle was more fatiguing. Leverett *et al.* (14) found the increase in arterial overshoot was directly correlated to the delay in its occurrence post-G.

As suggested, for heart rate and the EPS, arterial pressure likewise is an individual characteristic and, therefore, comparing arterial pressure responses between groups of different subjects is unreliable. Consequently, although lower arterial pressure overshoots post-G were found with the pilots compared with the SAM subjects, this does not necessarily indicate a greater level of fatigue with the SAM subjects.

Subjective analysis:

According to B. O. Hartman (VNE/SAM) and Janssen and Docter (12), the development of fatigue and its recovery after a stressful exposure may be readily quantified using subjective assessment. These subjective data, as determined using fatigue cards (Fig. 3) for all three groups relative to seatback angle, are shown in Table XI.

The subjects after experiencing either HSG or the SACM, and pilots exposed to the SACM, all found the 40° seatback angle less fatiguing, yet this was statistically significant only in the HSG group.

The pilots demonstrated greater fatigue following the SACM than did the SAM subjects. Germane to these findings is that the pilots were required to perform all three SACMs on the same day, which resulted in an accumulation of fatigue; e.g., the pilots' mean fatigue scores relative to their exposure number were, a) exposure 1 = 5.25 (similar to the mean scores for our SAM subjects); exposure 2 = 4.0; and, exposure 3 = 3.0. Considering individual pilot data, a regression analysis was performed using their fatigue scores (F) and exposure numbers (E):

$$F = 6.3 - 1.12\,E \qquad \text{(Eq. 1)}$$
$$r = 0.54,\ p<0.10$$

This equation suggests that between five and six repeated exposures (5.6 exposures) of the SACM in the

TABLE XII. COMFORT (SUBJECTIVE DATA) OF THE SUBJECTS DURING G RELATIVE TO SEATBACK ANGLE (MEAN ± S.E.). HIGH SCORE INDICATES LOW COMFORT.

		Seatback Angle		
G exposure	N*	23°	28°	40°
SACM	8	5.6 ± 0.86	4.0 ± 1.1	2.9 ± 0.83
HSG	5	5.4 ± 1.6	4.4 ± 1.2	5.2 ± 1.3
SACM**	4	5.8 ± 1.7	4.3 ± 1.1	3.3 ± 1.3

* N = Number of subjects per group.
** Pilots were subjects.

TABLE XIII. ACCEPTANCE BY THE SUBJECTS AFTER EXPOSURE TO THE 3 SEATBACK ANGLES—1 INDICATES THE PREFERRED SEAT.

	Seatback Angle		
Subject	23°	28°	40°
RK	2	1	3
JK	3	2	1
JR	3	2	1
DE	3	1	2
CK	3	2	1
SS	3	1	2
MM	1	2	3
DS	2	3	1
mean	2.5	1.8	1.8
S.E.	0.27	0.25	0.31

same day with 20-min rest periods would produce a maximum fatigue score of 0. Interestingly, at Nellis AFB, Nv, where we obtained our SACM profile, a maximum of 5 ACMs are performed during a single mission; and it has been observed by S. D. Leverett, Jr. (VNB/SAM) that the pilots return in a rather fatigued state.

Fatigue recovery appeared to be nearly complete, the subjects and pilots returning to a near-refreshed state (Fig. 3) after 20 min resting quietly at 1 G (Table XI). However, even though these men felt "refreshed," it is obvious that they retained some degree of fatigue or their fatigue resistance was reduced inasmuch as fatigue became progressively more severe as observed in the pilots following a series of three repeated SACMs (Eq. 1).

Comfort

Man is never really comfortable while exposed to high G so, in essence, we are really measuring the least amount of discomfort. Mean "comfort" scores for the SACM by the SAM subjects and pilots were quite similar (Table XII)—the 40° seatback angle generally was more comfortable during G exposure than was the 28° or 23° seatback angle, although not statistically significant (paired t-test). Quite obviously, the reason for this lack of statistical significance is the high degree of variability of seat comfort among subjects; e.g., one SAM subject considered the comfort of the 23° seatback angle superior to either the 28° or 40° seatback angle. On the other hand, none of the back angles were superior regarding comfort during HSG exposure.

Comfort in an aircraft seat, however, should probably be decided while the individual is at 1 G since, obviously, the majority of time that the seat is occupied during flight is in noncombat (1 G) situations.

Seat Acceptance

This determinant was an attempt for both the pilots and SAM subjects to subjectively evaluate the combination of comfort, fatigue and its recovery, and effort during the SACM relative to seatback angle *only*. All of the pilots preferred the 40° seatback angle. However, the SAM subjects preferred equally the 40° and 28° seatback angles—one subject preferred the 23° seatback angle (Table XIII).

DISCUSSION

This type of study, where specific answers are sought regarding pilot's capabilities in a highly maneuverable aircraft, requires compromise between the rigidity of the well-controlled laboratory and the flexibility of the "real-world" flying environment. Accordingly, we have attempted to bring the "real-world" into the dynamic laboratory of the centrifuge by using test pilots and a variable G profile which simulates an aerial combat maneuver (SACM) appropriate for the fighter aircraft under consideration. In addition, in order to relate to the physiologic and performance data obtained from

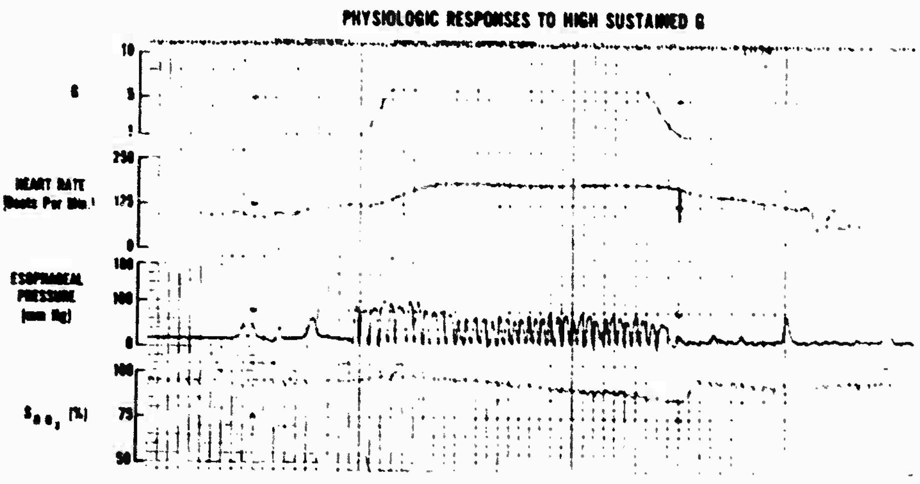

Fig. 6. An example of three physiologic responses (heart rate, esophageal pressure, arterial saturation) of one subject exposed to HSG (6 G for 60 s).

these pilots exposed to the SACM, we have compared these data with data obtained from techniques more traditional with acceleration studies; viz a) experimental subjects whose only experience with G has been obtained in the laboratory of the centrifuge; b) high sustained G exposures; and c) "relaxed" G tolerances.

Our experimental subjects' physiologic responses were similar to those of the pilots where comparisons were possible—the experimental subject appears to be an acceptable "model" for pilots in physiologic studies of this type.

The use of the SACM in this study in conjunction with the more conventional HSG type of high-G exposure proved that the SACM is an acceptable approach for acceleration research. Several differences in the physiologic responses to high G were found associated with these two types of G exposures. Three examples of (analog) physiologic parameters are found in Fig. 1 relative to the SACM, and these may be compared with the same parameters recorded during HSG as shown in Fig. 6. These physiologic parameters represent three types of responses to these two types of G profiles.

1) Esophageal pressure is directly correlated with the immediate G level; i.e., a dynamic parameter such as this is extremely sensitive to a change in G associated with the SACM—especially the high-G epochs of the SACM. Since the effort required to tolerate high G is a function of energy expenditure performing the M-1, it appears that for effort and fatigue parameters to be applicable to aircraft maneuvers an SACM-type exposure would be a requirement in an experiment using a centrifuge.

2) Arterial saturation, surprisingly, also appears to be a rather dynamic parameter although less so than Pes; i.e., Sao_2 could be classified as a moderately damped response relative to G.

3) Heart rate, on the other hand, appears to be a heavily damped physiologic response relative to changing G qualitatively and quantitatively, the mean heart rate response to HSG or the SACM is quite similar (Table III).

Consequently, it appears that greater application of physiologic data to aircraft maneuvers, where high G is frequently encountered, is possible if centrifuge data are obtained from SACM-type exposures.

Relaxed G tolerances frequently are of significant value in predicting the total benefits of anti-G methods or apparatuses used as high G. This may be surprising to some investigators since inherent relaxed G tolerances, even with the anti-G suit inflated, accounts only for approximately 50% of man's maximum $+G_z$ tolerance (6). In this study, regarding high-G tolerance for instance, relaxed G tolerances did accurately predict that large anti-G benefits were not probable with seatback angles <45°.

During high-G exposures, man in the 13° seatback angle must exert maximum physical effort (M-1) at high-G levels; e.g., in our experiment, 8 G. In some individuals, this effort was measured and found to be as high as 160 mm Hg. Unfortunately, the M-1 must start early in the beginning of the high-G exposure so that ample eye-level arterial pressure will be available at the highest G level attained. Consequently, for any anti-G method to be beneficial at high G, a significant increase in relaxed G tolerance with anti-G suit inflated—the authors would estimate an increase of at least 1 G—must be present before a subject feels that he can tolerate high-G levels (during an SACM) without a maximum M-1. According to Burns (2), a 1-G increase in relaxed tolerance would approximate a minimum reclined seatback angle of 55°; i.e., seatback angles ≧55° would offer much greater anti-G protection than found with seatback angles ≤45°.

G tolerance vs. G protection has been considered at some length by Burton and Krutz (4,5) who concluded that although some anti-G techniques increase the ability of man to tolerate G, his physiology during high G is altered drastically, possibly with pathologic consequences. On the other hand, the tilt-back seat of 65° allows man to tolerate high G with only moderate alterations in his physiology (2) offering increases in both G tolerance and G protection, while the 40° seatback angle did significantly reduce the expected increase in heart rate during high-G exposure (Table III). This effect on heart rate is important, pathologically speaking, since subendocardial hemorrhage associated with exposure to sustained G levels "tolerable" to man, as determined using adult miniature swine, appears to require a high heart rate (7).

The greater reduction in Sao_2 found in those men at a 40° seatback angle during the SACM may be of concern regarding both vision and performance. McFarland (15) measured the effect of arterial desaturation on impairment of performance of four visual functions and of six mental tests. He found "increasing serious impairment" (25% reduction) in visual functions beginning at 90% Sao_2 and mental functions starting at 86% Sao_2 for "attention" and 76% Sao_2 for "memory." Considering our group mean at 40° of 79.4% Sao_2, some of these men probably were suffering some temporary visual and mental impairment. The physiologic basis for this increase in reduction in Sao_2 associated with increasing seatback angles, if it is real, is not known.

Since our pilots assumed a more upright posture during the SACM, they were less hypoxic and only bordered on significant reductions in Sao_2. Repeated exposures to the SACM did not have an accumulative effect on the decrease in mean Sao_2 found in the four pilots, as might be expected with unresolved atelectatic conditions (evidence of absorption atelectasis following HSG exposure has been reported previously (6)) after the first and second exposures; viz exposure 1 = 84.3%; exposure 2 = 80.8%; and exposure 3 = 85.5%, Sao_2.

It should be remembered that the 28° and 40° seatback angles in this study incorporated the concept of the elevated lower legs and feet for additional anti-G benefits. However, it appears that this had no appreciable anti-G benefit; specifically, the failure of the elevated legs to increase relaxed G tolerance between the 23° (legs not elevated) and 28° (legs elevated) seatback angles (Table I). In fact, at 28° the relaxed G tolerances were slightly lower. Another consideration suggesting that the elevation of the legs and feet, in themselves, have no anti-G beneficial effect is that the mean heart rates found in the pilots during the three SACMs were not different between seatback angles. Although the pilots did not sit back in the seats, they did elevate their legs during the 28° and 40° exposures.

The subjective data regarding comfort, fatigue and its recovery, and effort during high-G exposure does suggest some anti-G benefits relative to the 40° seatback angle, but these data may have been influenced by preconceived thoughts; all of the pilots whom we interviewed were very excited about this 30° seatback angle and could have subconsciously biased their subjective data. On the other hand, the subjective data from our SAM subjects were qualitatively similar to those of the pilots and it was apparent that the SAM subjects were not particularly keen on the 40° seatback angle before the experiment.

In summary, therefore, it appears that at a seatback angle of 40°, the major benefits are a reduction in the increase in heart rate usually found during high-G exposure and less subject fatigue with greater comfort. However, this cardiovascular G-protection is lost if the subjects or pilots sit upright in these experimental seats and do not take advantage of the increased back angle.

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